BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING

Summary Report

SPR 387.011

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by

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16. Abstract

Small, concrete beams with no steel reinforcement were externally strengthened with eight different configurations of fiber reinforced polymer composites. The reinforcement configurations consisted of high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers. Load capacity tests were conducted for all eight configurations, and fatigue tests were conducted for two of the configurations. Beams with the higher modulus epoxy had more load capacity than beams with the lower modulus epoxy. However, this enhancement decreased as the failure mode changed from flexural failure to less desirable failure modes. The modulus of the resin had no effect on beam stiffness. The fatigue strength of the beams was strongly dependent on the load capacity of the beams; consequently, higher modulus epoxy could improve the fatigue performance of concrete beams.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

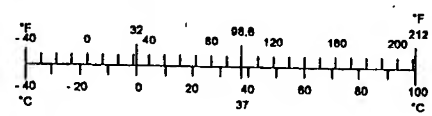
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

(4-7-94 jbp)

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DISCLAIMER

BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING

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1.0 INTRODUCTION

Externally applied fiber reinforced polymer (FRP) composites applied as a wet lay-up are increasingly being used to strengthen, repair, and rehabilitate civil structures. Performance of a structure with composites depends on the structural design and the orientation, properties, and proportion of the constituents (fibers and polymer resin). In the case of a wet lay-up, the matrix resin is also the resin that bonds the composite laminate to the structure. The resin is critical for effectively transferring strain to the composite over the life of the structure. Design engineers can choose from many composite systems with a wide range of resin properties. It is unclear, however, whether there are resin and fiber combinations that perform better than others.

A study conducted by Oregon State University and funded by Oregon Department of Transportation investigated the effects of different epoxy resin and fiber combinations on the static and cyclic behavior of small, concrete beams strengthened with FRP composites. The results of that study are reported in a masters project report from the Department of Civil, Construction, and Environmental Engineering at Oregon State University (*Seamanontaprinya, 2001*). This report is a summary of that thesis.

2.0 METHOD

2.1 STATIC LOAD TESTING

Thirty-eight unreinforced concrete beams were cast with dimensions 150 mm x 150 mm x 530 mm, using concrete with a nominal 28-day strength of 32 MPa. Twenty-four beams were reinforced with eight composite strengthening configurations using high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers, as shown in Table 2.1.

Table 2.1: Composite configurations for static load tests

Identification	Composite Configuration	Number of FRP Layers	Number of Specimens
CONT	Unreinforced concrete beam	0	3
1LG	Low-modulus resin with glass fiber	1	3
2LG	Low-modulus resin with glass fiber	2	3
1LC	Low-modulus resin with carbon fiber	1	3
2LC	Low-modulus resin with carbon fiber	2	3
1HG	High-modulus resin with glass fiber	1	3
2HG	High-modulus resin with glass fiber	2	3
1HC	High-modulus resin with carbon fiber	1	3
2HC	High-modulus resin with carbon fiber	2	3
			Total: 27

Mitsubishi Epotherm® L700S resin was used for the low modulus epoxy, and Tyfo® S resin was used for the high modulus epoxy. Glass fiber from the Fyfe Corporation – Tyfo® SHE-51 – was used as the low modulus fiber; and carbon fiber from the Fyfe Corporation – Tyfo®SCH-41 – was used as the high modulus fiber.

These beams, along with three unstrengthened control beams, were loaded to failure in third-point loading in accordance with ASTM C78, as shown in Figure 2.1 (*ASTM 2001*).

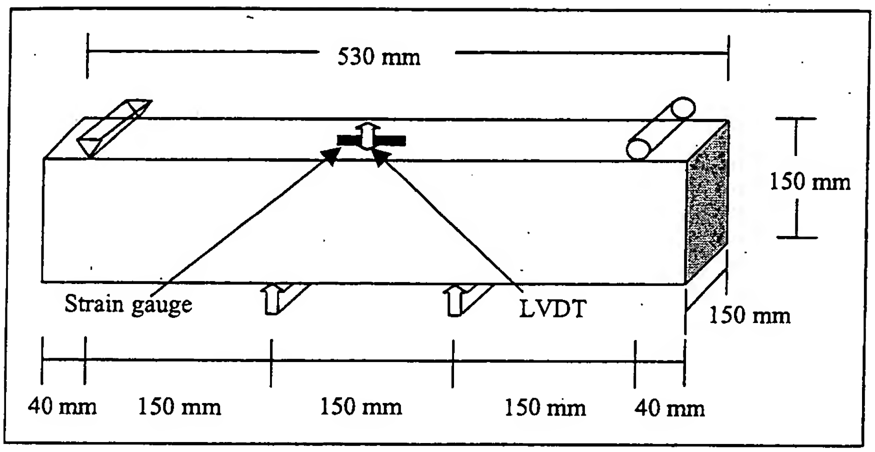

Figure 2.1: Test configuration

2.2 FATIGUE TESTING

The remaining 10 beams were reinforced with two composite strengthening configurations, as shown in Table 2.2.

Table 2.2: Composite configurations for fatigue tests

Identification	Composite Configuration	Number of FRP Layers	Number of Specimens
CONT	Unreinforced concrete beam	0	1
1LG	Low-modulus resin with glass fiber	1	5
2HC	High-modulus resin with carbon fiber	2	5
			Total: 11

These beams, along with one unstrengthened control beam, were fatigue tested at 0.5 Hz under the third-point loading shown in Figure 2.1. The minimum load for each test was maintained at 0.67 kN (150 lb). The 1LG configuration was the low stiffness and strength condition, while the 2HC configuration was the high stiffness and strength condition of the eight composite combinations.

3.0 RESULTS AND DISCUSSION

3.1 LOAD TESTS

The results of the load tests are summarized in Table 3.1, and the failure modes of the tests are described in Table 3.2.

Table 3.1: Results of load tests

Configuration	Load (kN)	Deflection (mm)	Strain (microstrain)	Post-Crack Stiffness (kN/mm)	Failure Mode
CONT	27 29 30 Mean = 29	0.04 0.05 NA Mean = 0.03	230 200 190 Mean = 210	0	Flexure
1LG	97 98 127 Mean = 107	3.23 3.27 4.43 Mean = 3.64	12500 11900 15500 Mean = 13300	20 19 20 Mean = 20	Flexure with FRP rupture
2LG	142 189 195 Mean = 175	2.99 3.79 3.78 Mean = 3.52	10200 13300 14900 Mean = 12800	36 41 42 Mean = 39	Shear and flexure
1LC	141 149 158 Mean = 149	2.28 3.17 3.09 Mean = 2.85	7800 8600 9000 Mean = 8500	47 35 38 Mean = 40	Shear and flexure
2LC	179 199 210 Mean = 196	1.97 1.86 2.48 Mean = 2.10	5400 5400 6100 Mean = 5600	74 88 67 Mean = 77	Shear
1HG	134 136 143 Mean = 138	4.23 4.70 5.29 Mean = 4.74	16400 16300 17100 Mean = 16600	23 20 18 Mean = 20	Flexure with internal shear failure of laminate
2HG	196 203 220 Mean = 206	3.96 4.69 4.13 Mean = 4.26	12600 14600 14600 Mean = 13900	42 35 42 Mean = 40	Shear and flexure. 2 failed with concrete crushing
1HC	159 171 174 Mean = 168	3.38 3.46 3.13 Mean = 3.32	9600 11600 9300 Mean = 10200	38 38 42 Mean = 39	Shear and flexure. 2 had internal shear failure of laminate
2HC	196 201 223 Mean = 206	1.87 2.07 2.17 Mean = 2.04	5200 5400 6300 Mean = 5600	83 76 82 Mean = 80	Shear

Table 3.2: Failure modes

Failure Mode	Description
Flexure	Flexure crack develops from tensile side in the center of specimen between loading points and propagates to compression side.
Shear	Shear crack develops on the tensile side of specimen near support and propagates about 45° angle to the loading point.
Shear and flexure	Shear crack propagates to the center of specimen, shifts to flexure, and continues to propagate to the compression side.
Internal shear failure of laminate	Shear stress in the resin exceeds its capacity
Concrete crushing	Flexural cracking with concrete crushing on compression side.

As expected, beams with 2 layers of a particular fiber type had higher load capacity and stiffness than beams with 1 layer. Also, carbon fiber produced higher capacity and stiffness in the beams than the glass fiber. The resin had no effect on the stiffness; however, the high-modulus resin increased the load capacity up to 29%. A smaller increase in load capacity – as low as 5% – was observed when the failure mode switched from a desirable flexure failure to shear failure modes in beams strengthened with the higher stiffness composite configurations. This result indicated that for properly designed beams, the resin could appreciably affect the load capacity of the beam.

3.2 FATIGUE TESTS

The fatigue test results are shown in Table 3.3. Load ratios were calculated using the following equation:

$$R_1 = \frac{L}{L_{ult}} \tag{3-1}$$

where
R_l = load ratio,
L = applied load, and
L_{ult} = static ultimate loading capacity

Table 3.3: Fatigue test results

Configuration	Load Amplitude (kN)	Load Ratio	Number of Cycles	Failure Mode
CONT	29.0	1.000	1	Flexure
	22.2	0.766	136000	
1LG	107.0	1.000	-	Flexure
	72.8	0.680	80	
	64.3	0.601	180	
	55.5	0.519	1200	
	44.6	0.417	36000	
	40.0	0.374	648000	
2HC	206.0	1.000	-	Shear and Flexure
	105.0	0.510	11700	
	104.9	0.509	13700	
	89.1	0.433	32400	
	86.4	0.419	99800	
	81.0	0.393	916400	

Figure 3.1 shows that the higher strength and stiffness composite configuration, 2HC, provided better fatigue response. Figure 3.2 indicates that the fatigue strength of the composite-strengthened beams is strongly dependent on the capacity of the beams. Equations were established to predict fatigue life for the beams used in this study.

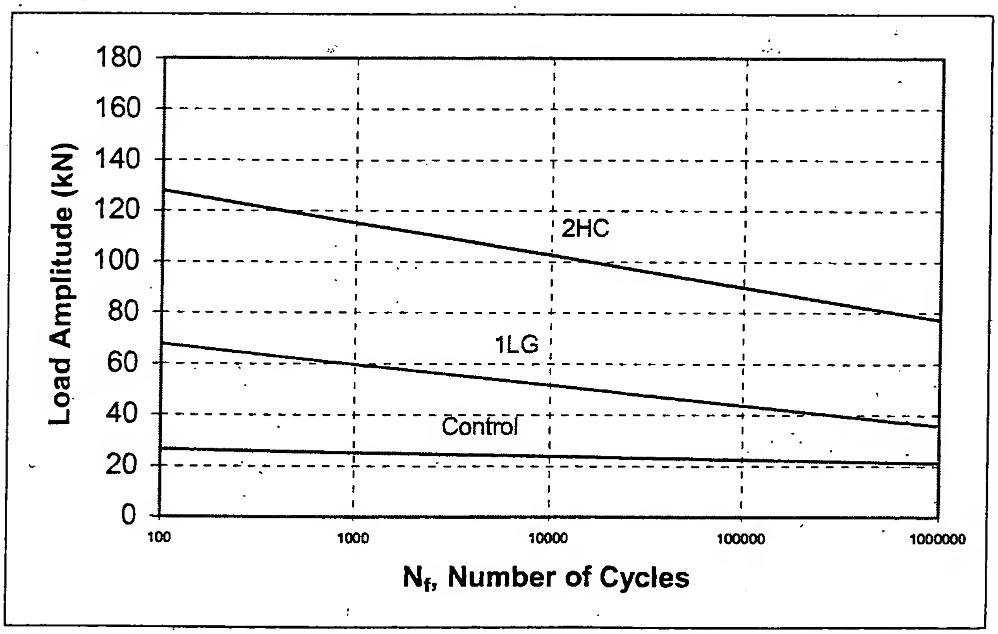

Figure 3.1: Load amplitude versus number of cycles

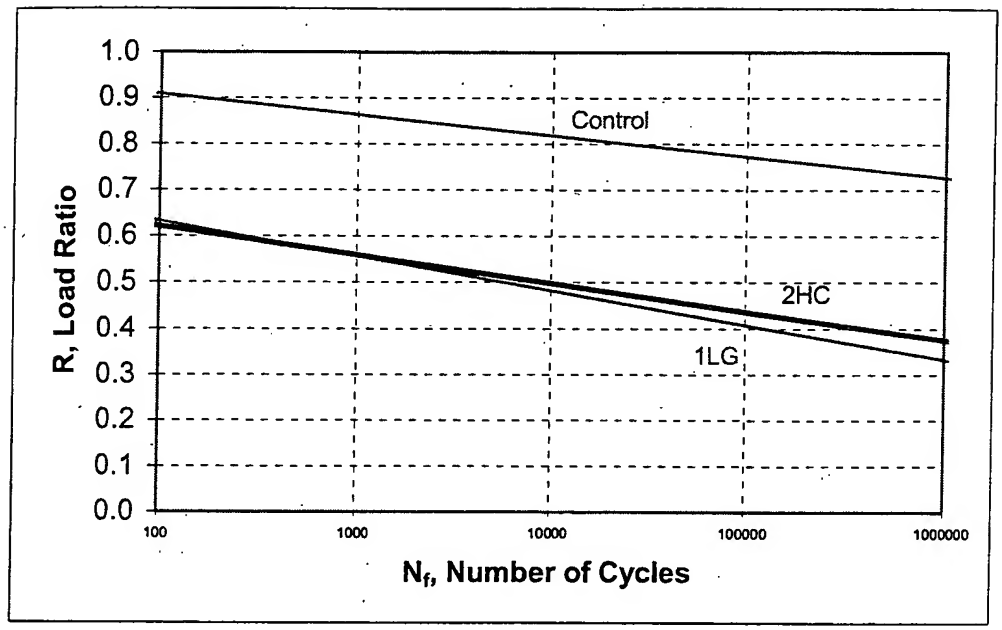

Figure 3.2: Load ratio versus number of cycles

4.0 CONCLUSIONS AND RECOMMENDATIONS

- Increasing the elastic modulus of the resin in a wet lay-up may increase the load capacity of FRP-strengthened, concrete beams. However, this enhancement decreases as the failure mode changes from flexural failure to less desirable failure modes.

- Because fatigue performance is dependent on load capacity, the resin effect may also increase the fatigue response of FRP-strengthened beams.

- The elastic modulus of the resin has no effect on the stiffness of beams.

- To verify and quantify the relationship between elastic modulus of the resin and performance, further testing would need to be conducted on full-size beams with realistic design configurations.

5.0 REFERENCES

American Society for Testing and Materials (ASTM) Subcommittee C09.61. 2001. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).* Designation ASTM C 78-00. West Conshohocken, PA.

Seamanontaprinya, Dharadon. 2001 (in press). *Behavior of FRP Composite-Strengthened Beams under Static and Cyclic Loading.* Masters project report, Department of Civil, Construction, and Environmental Engineering, Oregon State University.

TABLE 2.1 Typical Properties of Commercial Reinforcing Fibers

Fiber	Typical diameter (μm)[a]	Specific gravity	Tensile modulus, GPa (10^6 psi)	Tensile strength, GPa (10^3 psi)	Strain to failure (%)	Coefficient of thermal expansion (10^{-6} m/m per °C, 0–100°C)[b]	Poisson's ratio
Glass							
E glass	10 (round)	2.54	72.4 (10.5)	3.45 (500)	4.8	5	0.2
S glass	10 (round)	2.49	86.9 (12.6)	4.30 (625)	5.0	2.9	0.22
PAN-carbon							
T-300[c]	7 (round)	1.76	228 (33.5)	3.2 (470)	1.4	−0.1 to −0.5 (longitudinal) 7–12 (radial)	~0.2
AS[d]	7 (round)	1.77	220 (32)	3.1 (450)	1.2	−0.5 to −1.2 (longitudinal) 7–12 (radial)	
T-40[c]	6 (round)	1.81	276 (40)	5.65 (820)	2		
HMS[d]	7 (round)	1.85	344.5 (50)	2.34 (340)	0.58		
GY-70[e]	8.4 (bilobal)	1.96	483 (70)	1.52 (220)	0.38		
Pitch-carbon							
P-55[c]	10	2.0	380 (55)	1.90 (275)	0.5	−0.9 (longitudinal)	
P-100[c]	10	2.15	690 (100)	2.2 (325)	0.31	−1.6 (longitudinal)	
Kevlar 49[f]	11.9 (round)	1.45	131 (19)	3.62 (525)	2.8	−2 (longitudinal) +59 (radial)	0.35
Boron	140 (round)	2.7	393 (57)	3.1 (450)	0.79	5	0.2
SiC	133 (round)	3.08	400 (58)	3.44 (485)	0.84	1.5	—
Al_2O_3	20 (round)	3.95	379.3 (55)	1.90 (275)	0.4	8.3	

[a] 1 μm = 0.000039 in.
[b] 1 m/m per °C = 0.556 in./in. per °F.
[c] Amoco.
[d] Hercules Inc.
[e] Celanese.
[f] DuPont.

Engineering Mechanics of Composite Materials
1994 Oxford University Press, page 19-29

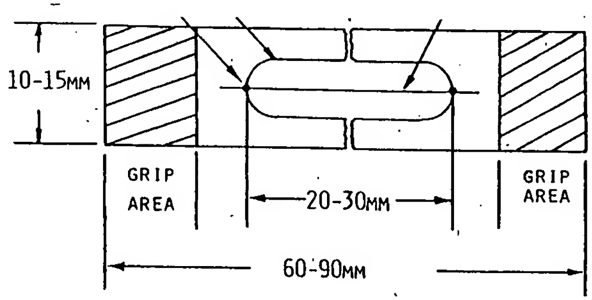

FIG. 2.2 Mounting tab for single filament testing (ASTM D3379-75).

grips of a tension testing machine, its midsection is either cut or burnt away. The tension test is carried out at a constant loading rate until the filament fractures. From the load-time record of the test, the following tensile properties are determined:

$$\text{Tensile strength } \sigma_{fu} = \frac{F_u}{A_f} \tag{2.1}$$

and

$$\text{Tensile modulus } E_f = \frac{L_f}{CA_f} \tag{2.2}$$

where: F_u = force at failure

A_f = average cross-sectional area, measured by a planimeter from the photomicrographs of filament ends

L_f = gage length

C = true compliance, determined from the chart speed, loading rate, and the system compliance

Similar tests can also be performed to measure tensile properties of fiber strands (either dry or resin impregnated). Generally, the average tensile strength and modulus of fiber strands are lower than those measured on single filaments.

Tensile stress-strain diagrams for all reinforcing fibers in use are linear up to the point of failure, as shown in Fig. 2.3. They also exhibit very low strains to failure and a brittle failure mode. Although the absence of yielding does not reduce the load-carrying capacity of the fibers, it does make them prone to damage in handling as well as during contact with other surfaces. In continuous manufacturing operations, such as filament winding, frequent fiber breakage resulting from such damages may slow the rate of production.

The high tensile strengths of the reinforcing fibers are generally attributed to their filamentary form in which there are statistically fewer number

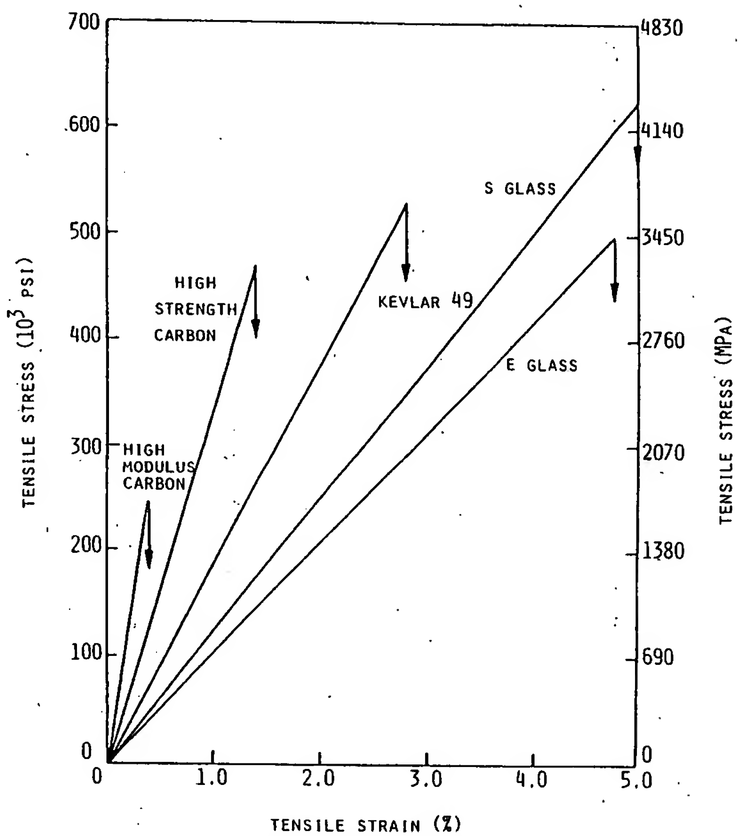

FIG. 2.3 Tensile stress-strain diagrams for various reinforcing fibers.

Table 2.4 Advantages and Disadvantages of Reinforcing Fibers

Fiber	Advantages	Disadvantages
E-glass, S-glass	High strength Low cost	Low stiffness Short fatigue life High temperature sensitivity
Aramid (Kevlar)	High tensile strength Low density	Low compressive strength High moisture absorption
Boron	High stiffness High compressive strength	High cost
Carbon (AS4, T300, C6000)	High strength High stiffness	Moderately high cost
Graphite (GY-70, pitch)	Very high stiffness	Low strength High cost
Ceramic (silicon carbide, alumina)	High stiffness High use temperature	Low strength High cost

Table 2.5 Fiber Properties

Type	Manufacturer	Tensile strength MPa (ksi)	Modulus GPa (Msi)	Density (g/cm^3)
E-glass	Corning	3,450 (500)	72.5 (10.5)	2.54
S-glass	Corning	4,480 (650)	85.6 (12.4)	2.49
Carbon				
AS4	Hercules	3,730 (540)	235 (34)	1.81
T300	Union Carbide	2,760–3,450 (400–500)	228 (33)	1.76
HTS	Hercules	2,830 (410)	248 (36)	1.82
IM-6	Hercules	4,480 (650)	290 (42)	1.80
IM-7	Hercules	5,170 (750)	290 (42)	1.80
Graphite				
T-50	Union Carbide	2,070 (300)	393 (57)	1.67
GY-70	Celanese	1,725 (250)	517 (75)	1.86
Pitch, type P	Union Carbide	1,725 (250)	345 (50)	2.02
Boron	AVCO	3,280–3660 (475–530)	365–414 (53–60)	2.1–3.0
Kevlar (aramid)	DuPont	3,800 (550)	131 (19)	1.45
Silicon carbide				
5.6 mil/C (SCS-2)	Textron	4,140 (600)	400 (58)	3.05
Nicalon	Nippon Carbon	2,070 (300)	172 (25)	2.60
Alumina				
FP-2	Dupont	1,725 (250)	380 (55)	3.70
Nextel 610	3M	1,900 (275)	370 (54)	3.75
Saphikon	Saphikon	3,100 (450)	380 (55)	3.80
Silica	—	5,800 (840)	72.5 (10.5)	2.19
Tungsten	—	4,140 (600)	414 (60)	19.3

composite and high moisture absorption. Boron fibers, not widely used at present, are useful in local stiffening applications because of their high stiffness.

Carbon (graphite) fibers come in many types with a range of stiffnesses and strengths, depending on the processing temperatures. High strength and high stiffness carbon fibers (AS4, T300, C6000), are processed at temperatures between 1200° and 1500°C (2200° and 2700°F). Ultrahigh stiffness graphite fibers (GY-70, Pitch) are processed at temperatures between 2000° and 3000°C (3600° and 5400°F). The increase in stiffness is achieved at the expense of strength, as shown in Table 2.5. Ceramic fibers such as silicon carbide and aluminum oxide have high stiffness and moderate strength and are used in metal–matrix and ceramic–matrix composites for high temperature applications.

Most fibers behave linearly to failure, as shown in Figure 2.8. Carbon fibers, such as the AS4 fiber, however, display a nonlinear stiffening effect. One important property of the fiber related to strength and stiffness is the ultimate strain or strain to failure, because it influences greatly the strength of the composite laminate.

As mentioned previously, the basis of the superior performance of composites lies in the high specific strength (strength to density ratio) and high specific stiffness (modulus to density ratio). These two properties are controlled by the fibers. A two-dimensional comparative representation of some typical fibers from the point of view of specific strength and specific modulus is shown in Figure 2.9.

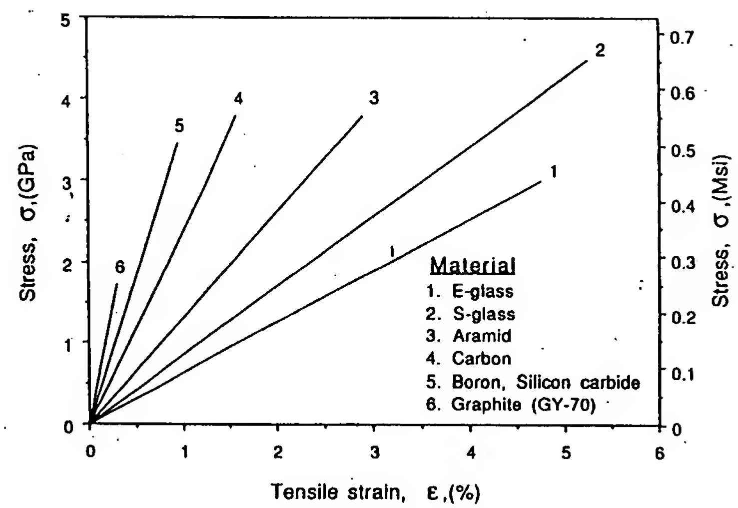

Fig. 2.8 Stress–strain curves of typical reinforcing fibers.

FYFE Co. LLC "THE FIBRWRAP® COMPANY"

Tyfo® SEH-51 Composite
using Tyfo® S Epoxy

DESCRIPTION
The Tyfo® SEH-51 Composite is an ICBO ER-5282 listed material comprised of Tyfo® S Epoxy and Tyfo® SEH-51 reinforcing fabric. Tyfo® SEH-51 is a custom weave, uni-directional glass and aramid hybrid fabric used in the Tyfo® Fibrwrap System. The glass material is orientated in the 0° direction with aramid fibers at 90°. The Tyfo® S Epoxy is a two-component epoxy matrix material for bonding applications.

USE
Tyfo® SEH-51 Fabric is combined with Tyfo® epoxy material to add strength and ductility to bridges, buildings, and other structures.

ADVANTAGES
- ICBO ER-5282 listed material
- Good high & low temperature properties
- Long working time
- High elongation
- Ambient cure
- 100% solvent-free
- Rolls can be cut to desired widths prior to shipping

COVERAGE
Approximately 675 sq. ft. surface area with 3 to 4 units of Tyfo® S Epoxy and 1 roll of Tyfo® SEH-51 Fabric when used with the Tyfo® Saturator.

PACKAGING
Order Tyfo® S Epoxy in 55-gallon (208L) drums or pre-measured units in 5-gallon (19L) containers. Order Tyfo® SEH-51 Fabric in 54" x 150 lineal feet (1.4m x 45.7m) rolls. Typically ships in 12" x 13" x 64" (305mm x 330mm x 1626mm) boxes.

EPOXY MIX RATIO
100.0 component A to 42.0 component B by volume. (100 component A to 34.5 component B by weight.)

SHELF LIFE
Epoxy - two years in original, unopened and properly stored containers.
Fabric - ten years in proper storage conditions.

STORAGE CONDITIONS
Store at 40° to 90° F (4° to 32° C). Avoid freezing. Store rolls flat, not on ends, at temperatures below 100° F (38° C). Avoid moisture and water contamination.

CERTIFICATE OF COMPLIANCE
- Will be supplied upon request, complete with state and federal packaging laws with copy of labels used.
- Material safety data sheets will be supplied upon request.
- Possesses 0% V.O.C. level.

502 Tyfo® SEH-51

TYPICAL DRY FIBER PROPERTIES

Tensile Strength	470,000 psi (3.24 GPa)
Tensile Modulus	10.5×10^6 psi (72.4 GPa)
Ultimate Elongation	4.5%
Density	0.092 lbs./in.^{3} (2.55 g/cm^3)
Weight per sq. yd.	27 oz. (915 g/m^2)
Fiber Thickness	0.014 in. (0.36mm)

COMPOSITE GROSS LAMINATE PROPERTIES

PROPERTY	ASTM METHOD	TYPICAL TEST VALUE	DESIGN VALUE*
Ultimate tensile strength in primary fiber direction, psi	D-3039	83,400 psi (575 MPa) (4.17 kip/in. width)	66,720 psi (460 MPa) (3.3 kip/in. width)
Elongation at break	D-3039	2.2%	2.2%
Tensile Modulus, psi	D-3039	3.79×10^6 psi (26.1 GPa)	3.03×10^6 psi (20.9 GPa)
Ultimate tensile strength 90 degrees to primary fiber, psi	D-3039	6,250 psi (43 MPa)	5,000 psi (34.4 MPa)
Laminate Thickness		0.05 in. (1.3 mm)	0.05 in. (1.3mm)

* Design and specification values will vary based on individual project requirements and applicable safety factors. Contact Fyfe Co. LLC engineers to determine appropriate specification values.

EPOXY MATERIAL PROPERTIES

Curing Schedule 72 hours post cure at 140° F (60° C).

PROPERTY	ASTM METHOD	TYPICAL TEST VALUE*
Tg 140°F (60°C) Post Cure (24 hours)	ASTM D-4065	180°F (82°C)
Tensile Strength[1], psi	ASTM D-638 Type 1	10,500 psi (72.4 MPa)
Tensile Modulus, psi	ASTM D-638 Type 1	461,000 psi (3.18 GPa)
Elongation Percent	ASTM D-638 Type 1	5.0%
Flexural Strength, psi	ASTM D-790	17,900 psi (123.4 MPa)
Flexural Modulus, psi	ASTM D-790	452,000 psi (3.12 GPa)

Testing temperature: 70°F (21°C) Crosshead speed 0.5 in. (12mm)/min. Specimens 2716-0255 - 20 ...
* Specification values can be provided upon request.